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Environmental life cycle assessment of industrial high-temperature to residential small-size heat Pumps: A critical review

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ABSTRACT

The decarbonization process of the industry and the heating sector, underway in Europe, directly involves heating, cooling, ventilation, and air conditioning systems. In this context, heat pump technologies play a key role in having the ability to be powered by decarbonized energy carriers (i.e., electricity from renewables for vapor compression cycle, hydrogen for absorption cycle, etc.), as well as harnessing renewable or waste heat, in different applications (i.e., industry, district heating networks, and civil sector). The European Commission considers the life cycle assessment method one of the leading methodologies for environmental metrics. Many scientific studies related to analyzing the environmental profile of heat pumps have been written using this method. With the aim to investigate the outcomes achieved and modeling approaches applied, this study reviews existing environmental life cycle assessment studies of (i) high-temperature, (ii) large-size (over 300 kW_{th}), and (iii) medium and small-size heat pumps. In total, 19 articles containing 637 scenarios were found in the literature to be relevant to the research aim. The study analyzes different heat pump technologies (i.e., vapor compression, absorption, and indirect Stirling cycles). The analysis shows that the use phase is the main contributor: (i) average value of 94.6% for the global warming potential, (ii) 69.9% for abiotic depletion potential indicator (metals and minerals). The analysis reveals that life cycle assessment studies apply a rather narrow approach and lack variability in modeling. For future research, it is recommended that the thermodynamic behavior of the heat pumps be properly simulated or monitored. In addition, a stochastic evaluation shall be included in the analysis to reduce and highlight the uncertainty of the results, especially the global sensitivity analysis. Finally, high-temperature heat pumps shall also be investigated using the consequential approach to understand better the environmental consequences of installation in an industrial production process.

1. Introduction

The European Union (EU) set aspiring targets to reduce Greenhouse Gas (GHG) emissions and reach neutrality by 2050 in the Green Deal [1]. In this regard, the European Commission proposes a set of packages to revise and update EU legislation and to achieve the set climate targets agreed by the Council and the European Parliament, i.e., Fit for 55 and REPowerEU [2,3]. The revised Renewable Energy Directive [4], entered into force in November 2023, aims to increase the share of renewables to 45 % by 2030.

To support renewables uptake in transport, heating, and cooling, it aims to create an energy-efficient, circular, and renewable energy system that facilitates renewables-based electrification and promotes renewable fuels, including hydrogen, in areas like transport or industry where electrification is not yet feasible.

The industry and residential sector are recognized as significant contributors, accounting for approx. 25 % of each of the final energy demand in Europe, according to the International Energy Agency (IEA) [5]. The decarbonization process of the industry and the heating sector, underway in Europe, directly involves Heating, Ventilation, and Air Conditioning (HVAC) systems.

High-Temperature Heat Pumps (HTHPs) are used in the industrial sector, mainly for waste heat recovery in process heat supply [6]. According to Arpagaus et al. (2018), HTHPs operate with a heat source temperature between 40 °C to 60 °C and a heat sink temperature of 80 °C to 100 °C. For Very High Temperature Heat Pumps (VHTHPs), the range is 60 °C to 120 °C and 100 °C to 160 °C for heat source and sink, respectively.

HTHPs and VHTHPs, now referred to as “HTHPs,” also have the

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Nomenclature

Subscripts

el	electric
th	thermal

Abbreviations

ALCA	Attributional Life Cycle Assessment
AP	Acidification Potential
APOS	Allocation at the point of substitution
CLCA	Consequential Life Cycle Assessment
DB	Database
DH	District Heating
EF	Environmental Footprint
EU	European Union
GHG	Greenhouse Gas
GS	Google Scholar
GWP	Global Warming Potential
HTHP	High-Temperature Heat Pump
IEA	Interational Energy Agency
IO	Input-Output
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LSHP	Large-Size Heat Pump
LPG	Liquified Petroleum Gas
MRM	Material Resources: Metals/Minerals
N/R	Not Relevant
N/S	Not Specified
OAT-SA	One-At-the-Time Sensitivity Analysis
pLCA	prospective LCA
rLCA	retrospective LCA
SSHP	Smal-Size Heat Pump
VHTHP	Very High-Temperature Heat Pump
WEEE	Waste Electrical and Electronic Equipment
WoS	Web of Science

potential for installation in District Heating (DH) networks due to high water delivery temperatures, allowing application even in 3rd-generation (3G) networks. The 3GDH network operates at a supply temperature of fluid over 80 °C, with the possibility of recovering waste heat at high temperatures. The electrification of the heat and DH networks is indicated in the European Union's (EU) strategic long-term vision as the main energy transition pathways [7]. The benefits of heat electrification could be summarized in a clean energy carrier, a highly developed transmission infrastructure compared with liquid fuels, very efficient and affordable technology (i.e., heat pumps), etc. DH is crucial for achieving ambitious climate targets, thanks to the ability of industrial and municipal waste heat recovery, flexibility by thermal storage, and integration of renewable sources.

Life Cycle Assessment (LCA) is an established method to quantify the environmental profile of products (i.e., goods and services). LCA is standardized by ISO 14040 and 14,044 [8,9] and can be considered a comprehensive and scientifically reliable method for environmental metrics [10].

LCA can be classified according to:

- The modeling approach in attributional (ALCA) and consequential (CLCA) [11–13]. The approach can be applied to Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) [14]. According to ISO 14044, LCI and LCIA are: (i) the phase where data are collected, the systems are modeled to quantify the relevant inputs and outputs of a product system, (ii) the phase in which the inventory data are associated with a specific environmental impact category and category indicators, respectively.
- The LCI modeling, turning in (i) process-based, (ii) input–output, and (iii) hybrid [15].

The ALCA and CLCA differ in their goals, i.e., research questions. The ALCA describes the environmental impacts of a specific product system is responsible for (i.e., *status quo*). CLCA describes the consequences of a decision (i.e., effect-oriented or change-oriented). Thus, the two research questions for the ALCA and CLCA are summarized by Hauschild et al. (2018):

- What environmental impact is the product responsible for?
- What are the environmental consequences of consuming the product?

Process-based, Input-Output (IO), and hybrid differ with respect to the LCI modeling:

- Process-based uses knowledge about the industrial processes taking part in a life cycle and the physical flows connecting them, i.e., a bottom-up approach to LCI modeling.
- IO models the product from a macroscale perspective, combining information on elementary flows associated with one unit of economic activity in different sectors and national statistics on the trade of products and services between sectors, i.e., a top-down approach to inventory modeling.
- Hybrid combines process-based and IO, providing a comprehensive sustainability assessment that merges the advantages of the two modeling approaches, i.e., high coverage of elementary flows and product resolutions for the process-based approach and no processes cut-off in the product system.

Due to the importance of heat pump technology as a solution for decarbonizing the industrial and heating sectors, this article critically analyzes the existing scientific papers on LCA. The authors aim to create a methodological guideline analyzing the application in the existing literature and how the different methodological approaches adopted affect the environmental profiles (i.e., the results). The drivers used to conduct the analysis are as follows:

(1) HTHPs with heat sink temperatures greater than or equal to 100 °C (with applications in the industry) [6].
(2) Large-Size Heat Pumps (LSHP) greater than 300 kW_{th} nominal heating capacity, with heat sink temperature between 50 °C and 100 °C (with application in district heating network).
(3) Medium and small-size heat pumps for civil application.

To the authors' best knowledge, no review is available on LCA of HTHPs or LSHPs. For the building sector with individual appliances (for single building units), Marinelli et al. (2019) [16] and Aridi et al. (2024) [17] reviewed LCA studies. Marinelli et al. (2019) reviewed 17 HP systems with applications in residential, commercial, and retail buildings. Aridi et al. (2024) reviewed 36 articles considering HPs in residential buildings and the associated environmental profiles. The two review articles fall into cluster No. 3, namely medium and small-size heat pumps. To make this work more innovative, the review for cluster No. 3 was limited to articles that adopted the consequential approach in modeling the heat pumps. Marinelli et al. (2019) and Aridi et al. (2024) did not cover this approach.

The novelty of this article consists in answering the following research questions:

(i) How many scientific articles have been published on HTHPs, LSHPs, and medium or small-size HPs?
(ii) How are the LCA methodological issues related to HP technology addressed in existing literature?
(iii) Which environmental profiles are reported in the literature for heat generated by the HPs investigated?

The authors found 19 papers, i.e., 6 on HTHPs, 10 on LSHPs, and 3 on small-size (lower than 20 kW_{th} of nominal heating capacity) HPs using consequential LCA (no articles were found for medium-size HPs up to 300 kW_{th}).

2. Material and methods

The scientific articles were found and analyzed as schematized in Fig. 1, following the protocol for Systematic Literature Review (SLR) called the "snowball approach" [18]. The literature review was implemented, starting with "watchwords" formulated from the research questions. The term "watchwords" is used to avoid confusing them with the "keywords" proper to the reviewed scientific articles (given by the authors). Several watchwords were used to avoid only capturing articles using specific terminology and missing works using slightly different terminology (see Table 1).

The authors matched the watchwords to (i) the title, abstract, and keywords of articles on the databases "Scopus" and "Web of Science," (WoS) and (ii) to the whole documents for "Google Scholar." The "snowball" of collected articles' references was conducted using the "ResearchRabbit" mapping tool. The research was limited to English-written works with a time-boundary constraint set in 2010 to simplify the research. 2010 was considered sufficiently conservative concerning the evolution of heat pump technology. The initial research based on watchwords resulted in 5 035 (3 263 + 788 + 984 = 5 035) documents (see Fig. 1).

Table 1
Watchwords used for literature review.

–	Condition among words (OR)		Condition among words (OR)
Watchwords used for literature review within titles, abstracts, and keywords of the articles	• heat pump • high temperature heat pump • large heat pump • large scale heat pump • district heating • energy system comparisons	(AND)	• sustainability • life cycle assessment • climate change • global warming • low carbon • environmental impact • environmental profile • decarbonization

3. Analysis and exclusion of articles

A script written in Python was created and used as a first selection of the articles proposed by the databases Scopus (3 263) and WoS (788). The script filtered the articles based on article keywords according to additional watchwords. The watchwords were defined by randomly analyzing the titles and article keywords of 600 papers out of 4 051 (3 263 + 788 = 4 051). The 600 articles cover approx. 15 % of the articles found in Scopus and WoS are considered to be a robust percentage. The query and watchwords used within article keywords were: *'heat pump' OR 'decarbonization' OR 'decarbonisation', OR 'footprint' OR 'environmental impact' OR 'life cycle' OR 'global warming potential' OR 'carbon neutral' OR 'gwp' OR 'climate neutral' OR 'carbon neutrality' OR 'ghg' OR 'climate change' OR 'lca'*, resulting in 1 634 papers (Scopus) and 617 papers (WoS), i.e., excluding 1 800 papers in total. The 984 papers found in Google Scholar were filtered, removing the articles already present in Scopus and WoS, resulting in 633 articles (i.e., excluding 351 papers).

After that, the articles were filtered by analyzing (i) the title, (ii) the abstract, and (iii) the introduction and conclusions, resulting in 10 articles (from Scopus), 12 articles (from Wos), 2 articles (from Google

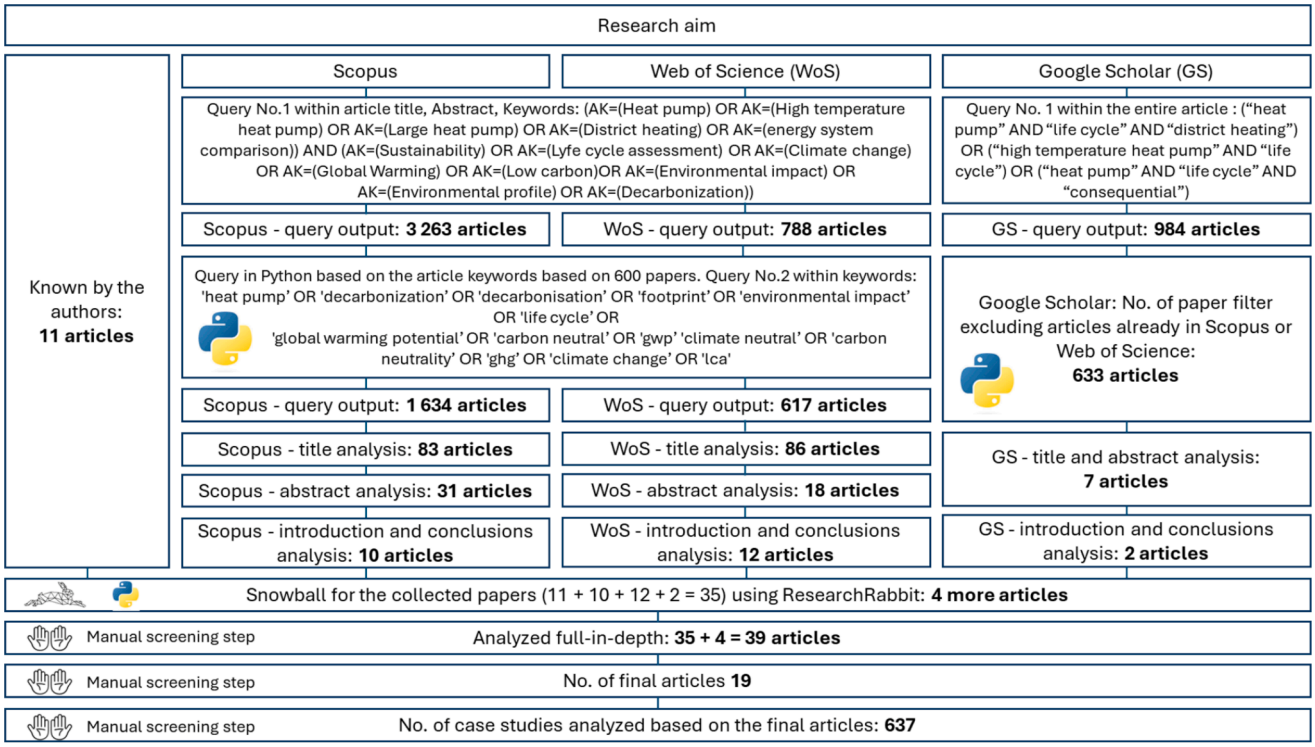

Fig. 1. Overview of the systematic literature review implemented.

Scholar), and 11 articles known by the authors, 35 articles in total. The filtering process was implemented by considering and evaluating that the papers met the following criteria. The study must be:

- Specific to HPs.
- Focused on environmental profile evaluations of HPs.
- Focused on HTHPs (with applications in industry), LSHPs (with applications in district heating networks and heat sink temperature between 50 °C and 100 °C) or be focused on small and medium-sized HPs evaluated using the CLCA.
- Providing sufficient information regarding the methodological approach used for the evaluation, which shall be based on the life cycle assessment method. For example, articles that deal with high-temperature heat pumps but do not adopt the life cycle assessment method as fully as were excluded, such as Dai et al. (2022) [19].

The criteria were applied conservatively, meaning that if, after reviewing the title, abstract, introduction, and conclusions, the authors were unsure whether to exclude the article, it was retained.

The snowball approach was applied to the 35 articles selected. The approach was conducted using the ResearchRabbit mapping tool, subdividing the 35 articles into three clusters:

(1) High-temperature heat pumps.
(2) Heat pumps with applications in district heating networks and heat sink temperatures between 50 °C and 100 °C.
(3) Medium and small-size heat pumps evaluated using CLCA.

The authors used the mapping tool to automatize the check of the reference lists in the 35 articles to ensure that no relevant sources were left out. Similar to this work, the tool suggested 4 878 articles with a time-boundary constraint set in 2010.

The 4 878 papers were then filtered using a Python script for removing the articles already analyzed at the beginning of the search procedure (i.e., outputs of the databases Scopus, WoS, and Google Scholar, 5 035 documents), resulting in 2 582 papers (i.e., excluding 4 878 – 2 582 = 2 296 works already analyzed as outputs of the databases).

Then, the articles were filtered using a Python script, using the same query applied to the articles found in Scopus and WoS. Still, in this case, it was based on titles (not to article keywords), i.e.,: *'heat pump' OR 'decarbonization' OR 'decarbonisation', OR 'footprint' OR 'environmental impact' OR 'life cycle' OR 'global warming potential' OR 'carbon neutral' OR 'gwp' OR 'climate neutral' OR 'carbon neutrality' OR 'ghg' OR 'climate change' OR 'lca'*, resulting in 972 papers.

After that, the articles were analyzed manually by (i) the title, (ii) the abstract, and (iii) the introduction and conclusions, resulting in 4 more articles that added to the 35 found before the snowball approach, making 39 documents in total.

The 39 articles were analyzed fully in-depth (manual screening step), and 19 documents relevant to the research aims were found. The final 19 articles are classified according to the three drivers of this paper:

- 6 articles that analyzed HTHPs [20–25].
- 10 articles that analyzed large-size HPs supplying DH network [23,26–34].
- 3 articles that evaluated small-size heat pumps for residential applications (small-size, up to 20 kW of nominal heating capacity). No articles were found for medium-size, i.e., from 20 to 300 kW, using CLCA modeling [35–37].

12 out of the 19 papers analyzed more than one scenario. In particular, the environmental profiles of the HPs were examined by changing:

- The operation configuration (i.e., source and sink temperatures).
- The geographical location.
- The refrigerant gas.
- The efficiency (i.e., coefficient of performances – COPs or Gas Utilization Efficiencies – GUEs).
- The capacity of the HPs.
- The estimated service life of the HPs, (vii) the time horizon, including prospective-LCA scenario for future HP applications.
- Comparing ALCA with CLCA modeling.

In particular, Jovet et al. (2022) analyzed 576 out of 637 scenarios (total of this paper) considering 24 European Union Member States, 2-time horizon scenarios (2030 and 2050), 2 refrigerant gases (R134a and R1336mzz(Z)), and 4 COPs associated with different production processes-applications linked with thermal lifts required in the manufacturing processes (i.e., 3.6 food industry, 4.6 alcohol production, 4.4 polycrystalline silicon, 3.7 poly film manufacturing, 5.7 ammonia production, and 3.8 chemical industry).

4. Case studies extraction and classification

The metadata from the case study scenarios were extracted from the analysis of the final articles. The information considered relevant for the

Table 2
Data extraction table categories.

Category	Description
Cluster	**(1) High-temperature heat pumps (HTHPs)** **(2) Large-size heat pumps (LSHPs)** **(3) Small-size heat pumps (SSHPs)**
Modeling descriptions	
LCA approach	Attributional (ALCA) and Consequential (CLCA)
LCI modelling	Input-Output, Process-based, and Hybrid modeling
LCA technology	Retrospective-LCA (rLCA) and prospective-LCA (pLCA)
Static and dynamic GWP	Static or dynamic characterization factors (timing related to CO_2eq emissions)
Deterministic and stochastic LCA	The result assessed with deterministic and stochastic (probabilistic, hypothesis test, etc.) analysis
Scope descriptions	
Functional unit (fU) or Reference Flow (RF)	Functional unit used for the LCA study (if specified)
Geographical region	Country of installation and operation of the appliances
Technical system boundaries (phases)	Cradle-to-grave and Gate-to-gate (Operational stage)
Technical system boundaries (Multi-functionality)	Exergy, energy, separate production, and substitution
Technology descriptions	
Thermodynamic cycle	Vapor compression (indirect Rankine), absorption, and indirect Stirling cycle
Sources	Air, groundwater, geothermal (soil), and waste heat
Thermal lift	Thermal lift temperature in °C
Coefficient of Performance (COP) or Gas Utilization Efficiency (GUE)	Values of COP and GUE
Heating capacity (P)	Nominal heating capacity of the HPs
Compressor type	Typology (if specified)
Working fluid	The working fluid used by the HPs
Leakage of refrigerant gas	Percentage of refrigerant gas leakages in the life cycle of the HP
Estimated Service Life (ESL)	The estimated service life of the HPs in years and operative hours
Results	
Background LCI database used	ecoinvent, GaBi, Environmental Footprint 2.0, and WEEE-LCI
Impact categories analyzed	Only Global Warming Potential (GWP) or GWP plus other impact categories
Heating technologies compared as a reference	Other technologies (i.e., natural gas boilers, etc.) used for the comparison

review is listed in Table 2 (see Metadata MS Excel file in Supplementary Material for further details). The scenarios were first classified according to the three drivers of this paper (i.e., cluster category in Table 2). Further, the data extraction table focuses on:

(i) The LCA approach.
(ii) LCI modeling.
(iii) LCA technology, i.e., if the inventory model represents a future state of a production system or not [38,39].
(iv) Static or dynamic LCI Global Warming Potential (timing related to CO_2eq emissions) as described by Levasseur et al. (2010) [40].
(v) Results evaluated deterministically and stochastically (i.e., results obtained were also assessed by error propagation).

The scope of each article is also listed, focusing on (i) functional units, (ii) geographical boundaries, (iii) technical system boundaries covered by life cycle stages considered, and approaches and methods to deal with multi-functionalities [41]. In this latter, the table refers to (i) separate production as an allocation method where the environmental burdens are partitioned according to the environmental profile of reference technologies for producing (separately) heat and electricity in combined heat and power plants and (ii) substitution as defined by ISO 14044. The categories analyzed also consider HP technologies, i.e.,

(i) The thermodynamic cycles.
(ii) The temperature of the sources, sinks, and thermal lifts.
(iii) The efficiencies (i.e., coefficient of performance and gas utilization efficiency).
(iv) Heating capacities, working fluids (with leakages), and estimated service life.

Finally, the table lists information on (i) background LCI databases, (ii) impact categories (focused only on GWP or extended to other impact categories), and (iv) heating technologies compared as a reference analyzed in the articles' scenarios.

5. Data standardization

The LCA results provided by the articles are analyzed and tweaked according to the different authors' functional units and characterization methods. This part of the research aims to compare the impact categories' results and provide distribution values related to the analyzed

Table 3
Modeling and scope descriptions of 19 reviewed LCA articles structured by clusters.

Authors	LCA approach	LCI modeling	rLCA or pLCA	Deterministic and Stocastic	fU	Technical boundaries	Multi-functionality	Geographical region
Cluster No. 1 – High-Temperature heat pumps								
Khan et al. 2020	ALCA	Process-based	rLCA	Deterministic	The appliance	Cradle-to-gate	Surplus for waste heat *	Sweden
Khan et al. 2021	ALCA	Process-based	rLCA	Deterministic	N/S	Cradle-to-gate	Surplus for waste heat *	Sweden
Jovet et al. 2022	N/S	Process-based	pLCA	Deterministic	N/S	Cradle-to-gate	Surplus for waste heat *	EU countries
Zeilerbauer et al. 2023	N/S	Process-based	rLCA	Deterministic	1 GJ	Cradle-to-gate	Surplus for waste heat *	Spain
Jovet et al. 2024	CLCA	Process-based	pLCA	Deterministic	Heat production over 1 year	Cradle-to-grave	Surplus for waste heat * and Substitution (DB)	Denmark and France
Högnabba et al. 2024	ALCA	Process-based	pLCA	Deterministic	Heat generated over 15 years	Cradle-to-grave	Surplus for waste heat *	EU countries
Cluster No. 2 – Large-size heat pumps								
Nitkiewicz et al. 2014	ALCA	Process-based	rLCA	Deterministic	1 GJ	Cradle-to-gate	N/S	Poland
Bartolozzi et al. 2017	ALCA	Process-based	rLCA	Deterministic	1 kWh	Cradle-to-grave	N/S	Italy
Famiglietti et al. 2021	ALCA	Process-based	rLCA and pLCA	Deterministic	1 kWh	Cradle-to-grave	N/R for HPs: substitution and surplus	Italy
Jeandaux et al. 2021	ALCA	Process-based	rLCA	Deterministic	1 GJ	Cradle-to-grave	N/R for HPs: surplus, exergy, and separate production	EU countries
Mahon et al. 2021	ALCA	Process-based	rLCA and pLCA	Deterministic	1 MWh	Cradle-to-grave	Energy and surplus *	Ireland
Pozzi et al. 2021	ALCA	Process-based	pLCA	Deterministic	1 kWh	Cradle-to-grave	N/S	Italy
Pratiwi et al. 2021	ALCA	Process-based	rLCA	Deterministic	1 MWh	Cradle-to-grave	Exergy	Switzerland
Spirito et al. 2021	ALCA	Process-based	rLCA	Deterministic	1 MWh	Cradle-to-grave	N/S	Italy
Famiglietti et al. 2022	ALCA	Process-based	rLCA	Deterministic	1 kWh	Cradle-to-grave	N/S	Italy
Pakere et al. 2022	ALCA	Process-based	rLCA	Deterministic	Heat produced yearly	Gate-to-gate	Surplus for waste heat and APOS (DB)	Latvia
Cluster No. 3 – Small-size heat pump (CLCA)								
Pedinotti et al. 2019	CLCA	Process-based	rLCA	Deterministic	N/S	Cradle-to-grave	Substitution	Germany
Naumann et al. 2022	ALCA CLCA	Process-based	rLCA	Deterministic	Heat generated over 20 years	Cradle-to-grave	Substitution (DB)	Quebec
Famiglietti et al. 2023	CLCA	Process-based	rLCA and pLCA	Deterministic and Stochastic	1 kWh	Cradle-to-grave	Substitution (DB)	EU countries

* Assumed by the authors based on the information reported within the article.
** Not Specified (N/S) and Not Relevant (N/R).
*** The term (DB) indicates that the substitution was used only for background processes, i.e., within the LCI database used for the analysis.

articles. The functional Unit (fU) selected for the comparison was 1 kWh_{th} generated by the heat pumps. However, as specified in Table 3, the papers assumed different fUs and, thus, are not directly comparable. The fUs were normalized, according to 1 kWh_{th}, after two screenings.

The first screening was based on the system boundary of the results, i.e., considering the impacts related only to the heat pumps and not, as in some cases, to the entire heating system where they are integrated (e.g., District Heating – DH). It is the case of Jeandeaux et al. (2021), Pakere et al. (2022), and Mahon et al. (2021), where the results are provided for the whole DH system. Pedinotti et al. (2019) report aggregated results for different building retrofit solutions (e.g., thermal insulation and air source heat pump) to a reference case. Therefore, extrapolating the impact relative to the heat pump system alone was not feasible. The authors retrieved the results for Spirito et al. (2021) and Famiglietti et al. (2022), although they did not provide specific outcomes for the evaluated heat pumps.

The second screening was performed according to the characterization method adopted. Only the articles containing midpoint impact categories are considered, hence excluding Khan et al. (2021 and 2020), Jovet et al. (2022 and 2024), and Nitkiewicz et al. (2014). The methods can be classified into the methodologies that list impact categories assigned to the inventory results (midpoint categories) and which can be further bundled into damage categories (endpoint categories). The midpoint outcomes were uninformed using the conversion factors provided by Rybaczewska-Błażejowska and Jezierski (2024).

6. Results and discussion

In this section of the article, the authors present and discuss the results obtained from the metadata extracted related to case study scenarios evaluated from the final articles (see Fig. 1). It was structured following what was reported in Table 2, classifying the findings per authors and cluster membership, i.e., (i) modeling and scope descriptions, (ii) technologies modeled by the articles investigated, and (iii) Life Cycle Impacts Assessment (LCIA) results highlighting the background LCI database and the characterization of methods used by the authors of the 19 articles founded and comparison with reference technologies (e.g., natural gas boilers, etc.). In the latter case, the results presented were normalized, as described in section 2.3. More information on the extracted metadata is provided in a Microsoft Excel file called “Extraction tables” in Supplementary Material.

6.1. Modeling and scope descriptions

The modeling and scope used by the authors of the final articles are highlighted in Table 3. The table presents for each article, (i) the cluster membership, (ii) the LCA approach (i.e., ALCA and CLCA), (iii) the LCI modeling, (iv) LCA technology (i.e., retrospective and prospective LCA), (v) if in the evaluation is included or not the uncertainty analysis via error propagation (stochastic), (vi) the functional Unit (fU) used, (vii) the approaches used to deal with the multi-functionalities, and (viii) the geographical region, i.e., country of installation and operation of the appliances.

6.2. Life cycle assessment (LCA) and life cycle inventory (LCI) modeling

The metadata analysis showed that all 19 papers are process-based LCA evaluations. None of the authors used Input-Output analysis or Hybrid LCA. Analyzing the LCA approach, 13 articles used the Attributional, 3 used the Consequential (Pedinotti et al. 2019, Famiglietti et al. 2023, Jovet et al. 2024), 1 used both approaches (Naumann et al. 2022), and 2 out of 19 did not specify which approach was used for the analysis.

It is highlighted that these conclusions were often obtained not directly from the text of the articles analyzed but by evaluating the background databases used (i.e., ecoinvent in the cut-off version, allocation at the point of substitution, or consequential, as will be better explained in Section 3.3) and the methods of handling multi-functionality, i.e., partition (allocation), surplus method, or substitution (system expansion).

In addition, the analysis revealed that just 1 (Jovet et al. 2024) out of 4 consequential analyses are related to cluster (1) High-Temperature heat pumps. The other 3 out of 4 are related to cluster (3) small-size heat pumps. This represents an important point of discussion for developing LCA analyses related to HTHPs.

As stated by Plevin et al. (2014) [42], ALCA is not designed to study the effect of changes in production systems. Still, it is typically applied to hot-spot identification and generic consumer information. On the contrary, CLCA examines how the relevant physical flows will change in response to a change in demand for the analyzed product; therefore, consequential models only include unconstrained, marginal suppliers, i.e., suppliers who can change their production volume due to increased demand [43].

HTHPs use waste heat, often from cogeneration systems, so the application of the CLCA approach would allow a better understanding of the environmental consequences of the decision related to the installation of an HTHP in an industrial production process related to higher demand for electricity supplied by the national grid, a Combined Heat and Power (CHP) plant, etc. (due to the HTHP can be electrically-driven appliances, i.e., vapor compression cycle) and potentially avoiding the discharge of waste heat, e.g., via dry cooler machines, i.e., a fluid cooler that uses air, a relatively dry, to accomplish process cooling.

6.3. Retrospective and prospective life cycle assessment

With the LCA (i.e., retrospective and prospective LCA – rLCA and pLCA), the authors consider if the papers analyzed any part inventory models represent a future state of a production system and, therefore, contain assumptions about future developments [39].

13 articles used rLCA, 3 used the pLCA [22,23,26], and 3 used both approaches [27,34,36]. In all cases, the pLCA is limited to the inventory used to determine the environmental profile of electricity used in the HPs. None of the authors extended the assessment to the other inventory processes of the product systems under evaluation, e.g., using PRospective EnvironMental Impact asSEment (premise) [44].

Among the articles using pLCA, only Jovet et al. (2024) and Famiglietti et al. (2023) did a CLCA. However, it is essential to clarify the life cycle inventories adopted. As introduced by Weidema et al. (2003) and discussed by Zamagni et al. (2012) [45], the main distinctions between CLCA and ALCA are: (i) processes are included to the extent of their expected change caused by a demand (affected processes), i.e., include market mechanisms into the analysis and (ii) co-products are handled by system expansion (substitution considering the marginal suppliers).

Unlike Jovet et al. (2024), which implemented a full CLCA, Famiglietti et al. (2023) performed a CLCA using the ecoinvent database with a system model “substitution, consequential, long-term” [46] except for the environmental profile of electricity used by vapor compression cycle heat pumps and the gas used by absorption cycle heat pumps. For these two processes, a pLCA was performed, i.e., proposing a future state of a production system (by scenarios). Still, they do not include the expected extent of electricity and gas change caused by future demand in the prospective scenarios (i.e., market mechanisms into the future). Thus, the analysis can be considered a semi-CLCA, as referred to by Schmidt (2010) [47], for those studies in which CLCA is not fully adopted concerning points (i) and (ii) described by Weidema et al. (2003).

6.4. Deterministic and stochastic analysis

The authors noted that only Famiglietti et al. (2023) also implemented an uncertainty analysis via error propagation to test the environmental result obtained (stochastic analysis). The uncertainties analysis followed the Monte Carlo (MC) simulation method. The consistency of the results achieved from the MC method was tested: (i) by

comparing the probability, i.e., comparing the results from the MC obtained for the product system under evaluation (typically used in commercial software), and (ii) by the null hypothesis test.

The hypothesis test (paired *t*-test) was implemented beyond the probability, evaluating the statistical comparability of the paired distributions among the assessed products, i.e., calculating the distance of the mean (μ) values (obtained with the MC) over the distance expressed in number of standard deviations (σ), see equation (1), and predicting the probability of committing a predetermined error value (α), generally not higher than 5 %, as described by Autelitano et al. (2023).

$$Z = \frac{\mu_1 - \mu_2}{\sigma/\sqrt{n}} \quad (1)$$

Where Z is the test score that is used to determine the probability of committing the error (using tables approximating the normal distribution), μ_1 and μ_2 are the mean values for the product 1 and 2 (to be compared), σ is the standard deviation, and n is the number of iterations of the MC analysis. This type of evaluation was carried out using the framework software Brightway 2.0 [48].

The analysis conducted in the other paper investigated is deterministic, i.e., without uncertainty analysis. In some cases, the authors implement, specifying directly in the text or through different analysis scenarios, the One-At-the-Time Sensitivity Analysis (OAT-SA). The OAT-SA consists of changing the value of uncertain factors one at a time while keeping the others constant [49].

Khan et al. (2020 and 2021) provide three outcomes changing the estimated service life of the HP (1, 8, and 15 years). Zeilerbauer et al. (2023) changed the refrigerant leakage %, HPs, and flash tank's mass. Mahon et al. (2021) implemented an OAT-SA varying the transport distances and geographic location of the system. Pedinotti et al. (2019) changed the characterization method from Impact 2022 + to ReCiPe 2016 [50,51]. Naumann et al. (2022) used the consequential system model of ecoinvent to validate the results.

The authors of this paper highlight that none of the papers investigated a global sensitivity analysis was performed. If the OAT-SA belongs to local sensitivity analysis, i.e., determines the effect of a (small) change in one of the input parameters at the time, the global sensitivity analysis is an extension of the uncertainty propagation. The global sensitivity analysis determines how much each parameter contributes to the output variance, thus emphasizing the unit processes and the elementary flows that contribute more to the final uncertainty of the study, permitting the highlighting of where the model can be improved. This aspect should be included in future LCA studies on heat pumps [52,53].

6.5. Functional unit and technical boundaries

The functional Unit (fU) is the quantified performance of a produced system used as a reference unit [9]. The majority of the authors are in line with the indications reported by Klöpffer and Grahl (2014) [54] and Hauschild et al. (2018), utilizing as fU a unit thermal energy generated by the HPs, i.e., 1 kWh (5 articles), 1 MWh (3 articles), and 1 GJ (3 articles) (see Table 3). Although the Joule is the unit for thermal energy in the International System of Units, the reason for using kWh or MWh may be related to applications in the building environment, where energy demand values are generally given in kWh, e.g., for energy performance certificates for European buildings – clusters No. 2 and No. 3 [55].

Kahn et al. (2021), Jovet et al. (2024), Högnabba et al. (2024), Pakere et al. 2022, and Naumann et al. (2022) provide the results considering the heat generated over a specific time horizon, i.e., in cases where the goal of the study is to assess the environmental profile of the machine or district heating network (excluding Jovet et al. (2024)), missing a proper definition of the functional unit. The fU is used to allow the comparison of different studies related to the same product category, thus generally referred to a unit value of the product function (i.e., 1 kWh, 1 MWh, 1 MJ, 1 GJ, etc. of heat), plus specifying other information answering the questions "What?", "How much?", "How well?", and "How long?" to permit a fair comparison between different alternatives [56].

The authors underline that, if in line with the goals of the study, functional units on an energy basis could be corrected by evaluating the heat delivered on an exergetic basis. It would normalize machine operating conditions by emphasizing the impacts embedded in generation systems and energy carriers.

Moving on to the description of the multi-functionality approaches adopted, it is crucial to analyze the articles about ALCA and CLCA. In fact, as mentioned in Section 3.1.2, the co-products should be handled by system expansion (substitution considering the marginal suppliers) in CLCA. Meanwhile, in the ALCA, co-products can be handled by substitution (considering the average suppliers) or partitioning (allocation). Of the 4 articles that adopt the CLCA, only Pedinotti et al. (2019) implement the substitution for the foreground (under the control of the authors) and the background data (derived from the Life Cycle Inventory database). The others implement the substitution using the ecoinvent library (system model "substitution, consequential, long-term"). In this regard, it is important to note that Jovet et al. (2024) did not adopt the substitution described by Waidema et al. (2003) for "not fully utilizing the dependent co-product" in this case, the waste heat used by the HTHPs. They adopted the surplus method, described by Heijungs and Suh (2002) [57], where minor flows do not receive any environmental burdens.

Fig. 2 shows the substitution applied for a generic "not fully utilizing the dependent co-product" case. In particular, the picture presents three products in output from a Combined Heat and Power (CHP) plant:

- Electricity, considered to be the determining product.
- Steam, considered to be a "full-utilized dependent co-product."
- Waste heat, considered to be a "not fully utilized dependent co-product."

To the best of the author's knowledge, electricity (W) is considered the determining product of the CHP installed in an industrial plant. This is because a change in demand for W affects the production volume of the activity (process A in Fig. 2). Q_1 is the dependent co-product; a change in demand for heat in the production process does not affect the CHP. It is provided using backup generators (e.g., boilers) for the plant's energy efficiency and economic reasons. Q_2 is considered the "not fully utilized dependent co-product." It is generally unused or used only if the best available technology, such as HTHPs, is installed.

Fig. 2 shows all the processes involved and the related flows in the Technosphere (i.e., that part of the environment that is made or modified by humans), plus the equations to assess the environmental profiles of the product involved in applying the substitution. In particular:

- Product W is assessed as the contribution of process A (CHP), minus the benefit related to the avoided marginal production of steam (process C – e.g., from a natural gas boiler), and plus the contribution of the process used to cool the waste-heat before disposing of it in the environment (process D – e.g., dry cooler machine).
- Product Q_1 is assumed to have the environmental profile of the marginal product (e.g., steam produced by natural gas boiler), plus process B (potential downstream activities, e.g., pressure reduction).
- Product Q_2 is assessed as the difference between process E (HTHP with electricity consumption) and process D (dry cooler with electricity consumption). Thus, the "not fully utilized co-product" in consequential modeling benefits from the avoided process D.

Of the 15 articles that adopt the ALCA, only Famiglietti et al. (2021) implement the substitution for the foreground (under the control of the authors—average production), which is not related to the HPs evaluated but to the environmental profile of the heat produced from a waste-to-energy plant supplied into a district heating network (reported as N/R

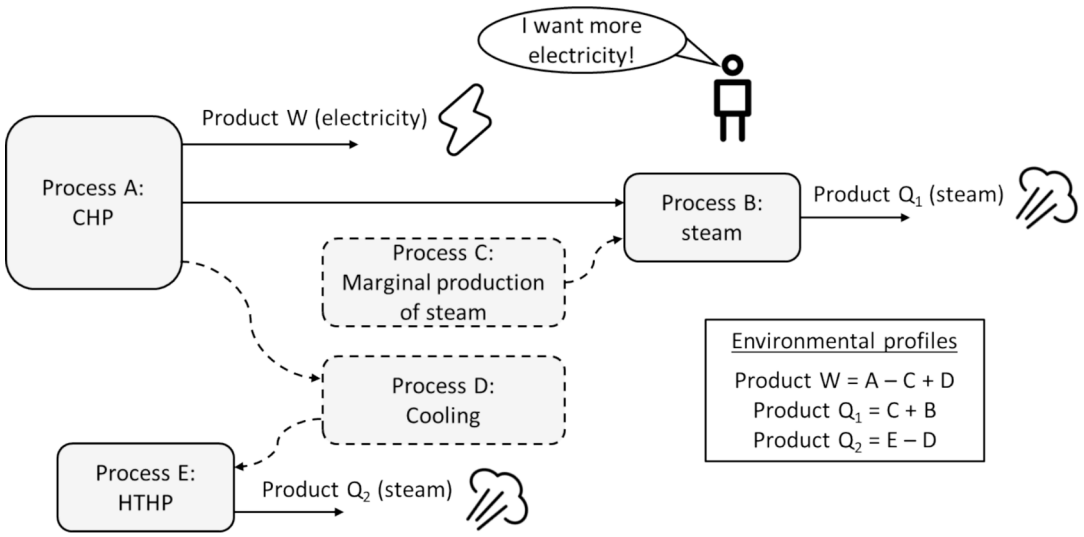

Fig. 2. Substitution applied to evaluate the environmental profile of steam produced by an HTHP. The dotted lines represent the substituted processes and related flows.

for HPs in Table 3).

Jeandaux et al. (2021) used to evaluate the environmental burdens of heat from a cogeneration plant, the surplus, the exergy, and the separate production partitioning method, as explained by Beretta et al. (2012) [58]. The surplus method is used by Famiglietti et al. (2021), in this case for waste heat from an industrial plant, and by other authors for waste heat in input to HTHPs, i.e., Kahn et al. (2020 and 2021), Jovet et al. (2022), Zeilerbauer et al. (2023), Högnabba et al. (2024), Mahon et al. (2021), and Pakere et al. (2022).

Pratiwi et al. (2021) use the exergy partitioning method to allocate the burdens between heating and cooling produced by the HPs. Mahon et al. (2021) use the energy method to evaluate the environmental profile of heat from a CHP fed in input to an HP.

Table 3 presents the multi-functionality column with a "Not Specified (N/S)" indication. This is because the articles do not explicitly provide information about the approach used for the foreground data; anyway, the authors confirm that all 15 articles use Life Cycle Inventory (LCI) databases (background) in accordance with the attributional approach.

The analysis reveals that the majority of the scenarios are from European countries. Fig. 3 presents two pie charts: Fig. 3 (a) shows the number of articles per cluster, highlighting the number of scenarios.

Cluster (1) presents more scenarios (600) related to 6 papers. In particular, (i) Jovet et al. (2022) analyzed 576 scenarios (24 European Union Member States, 2-time horizon scenarios, 2 refrigerant gases, and 4 COPs associated with different production processes), (ii) Jovet et al. (2024) evaluated 6 scenarios, (iii) Zeilerbauer et al. (2023) 4 scenarios, Khan et al. (2020 and 2021) 3 scenarios, and Högnabba et al. (2024) 8 scenarios.

Cluster (2) presents more articles (10) describing 22 scenarios in total. Cluster (3) is represented by 3 articles with 15 scenarios: 12 from Famiglietti et al. (2023), 2 from Naumann et al. (2022), and 1 from Pedinotti et al. (2019).

Fig. 3 (b) shows the geographical representation of the scenarios per article:

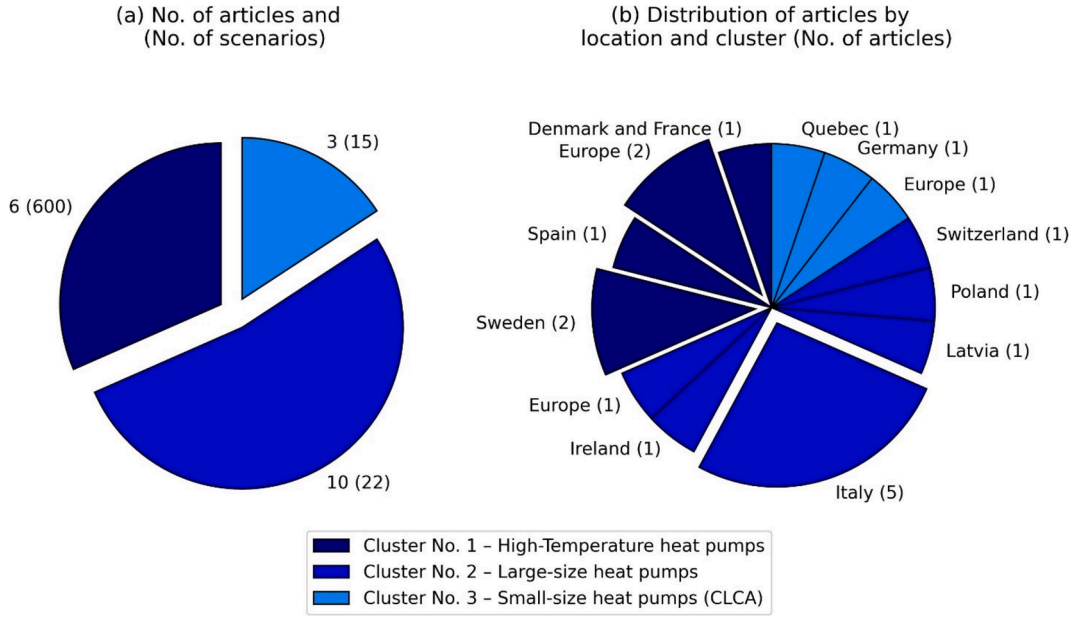

Fig. 3. Number of articles per cluster, highlighting (a) the number of scenarios and (b) the distribution of articles by country.

- 5 are based in Italy.
- 2 are in Sweden.
- 7 are in other EU Member States (i.e., Denmark, France, Germany, Ireland, Latvia, Poland, and Spain).

Finally, 1 is outside the political boundaries of Europe, i.e., Pratiwi et al. (2021) – Geneva (Switzerland), 4 are based on the geographical European boundaries (i.e., inside and outside the EU political borders), and 1 is based in North America (Quebec, Canada), i.e., Pedinotti et al. (2019).

Regarding the dynamic LCA approach, the authors did not find scenarios where timing was applied to the emissions related to the operational and end-of-life stages of the heat pumps. Timing, as explained by Levasseur et al. (2010), consists of using time-dependent characterization factors according to the time frame chosen for the analysis (i.e., the estimated service life of the machines) and the period covered by some impact categories (i.e., global warming potential and ozone depletion with a time horizon of 100 years, etc.).

6.6. Technology description

Table 4 presents the characteristics of the heat pumps included in the final list of articles. For each, the following information is shown:

13. Type of thermodynamic cycles.
14. Nominal heating capacities.
15. Coefficient of Performances (COPs) and Gas Utilization Efficiencies (GUEs).
16. Low-temperature heat source.
17. Type of working fluids and amount of leakages during the use phase of the HPs.
18. Thermal lift with source and sink temperatures.
19. Estimated Service Life (ESL).

For better readability, the data are grouped into three categories:

(1) HTHPs with supply temperature above 100 °C.
(2) LSHPs with capacity above 300 kW and supply temperature below 100 °C.
(3) SSHPs with capacity below 20 kW.

6.7. Thermodynamic cycles and nominal heating capacities

The heat pumps considered in the analyzed papers are based on three technologies:

- Vapor compression heat pumps are considered in 15 studies belonging to the three heat pump categories. The type of compressor

Table 4
Technology description.

Authors	Thermodynamic cycle	Nominal capacity (kW)	COP or GUE	Source	Temperature lift (°C) (source to sink)	Working fluid (leakages)	ESL (years)
Cluster No. 1 – High-Temperature heat pumps							
Khan et al. (2020)	Stirling cycle	500	2.0	Waste heat	105 (80/185)*	Helium gas – R704 (N/S)	1, 8, and 15
Khan et al. (2021)	Stirling cycle	500	2.0	Waste heat	105 (80/185)*	N/S (N/S)	1, 8, and 15
Jovet et al. (2022)	Vapor compression	5′000	3.6 to 5.7	Waste heat	48 to 28 (96/144) & (97/125)	R134a and R1336mzz(Z) (100 %)	20 and 8 000 h
Zeilerbauer et al. (2023)	Vapor compression	250	1.9 and 3.0	Waste heat	41 and 72 (80/121) & (80/152)	R1336mmz(Z) (modelled R134a) (15 %)	15 and 8 000 h
Jovet et al. (2024)	Vapor compression	N/S	5.0	Waste heat	N/S	CO_2 (5 % rate per y + 20 % at EoL stage)	Not specified
Högnabba et al. (2024)	Stirling cycle	750	1.8 and 2.3	Waste heat	141 and 77 (29/170) & (85/162)	Helium gas – R704 (N/S)	15
Cluster No. 2 – Large-size heat pumps							
Nitkiewicz et al. (2014)	Vapor compression Absorption	400 400	5.5 1.74	Groundwater	30 (20/50) 30 (20/50)	R134a (N/S) Water-ammonia (N/S)	10
Bartolozzi et al. (2017)	Vapor compression	1 500	4.2	Geothermal	15 (55/70)	N/S (N/S)	20
Famiglietti et al. (2021)	Vapor compression	300	4.0	Groundwater	42 (18/60)	R134a (103 %)	20
Jeandaux et al. (2021)	Vapor compression	5 000	6.3	Groundwater	10 (60/70)	R1234ze (N/S)	22
Mahon et al. 2021)	N/S	N/S	3.6	Waste heat	42 (28/70)	Water-ammonia (N/S)	20
Pozzi et al. (2021)	Vapor compression	4 000	4.5	Groundwater	N/S	R134a (103 %)	20
Pratiwi et al. (2021)	Vapor compression	7 200	9.67	Groundwater	7 (60/67)	R1234ze (105 %)	30
Spirito et al. (2021)	Vapor compression	6 000 to 20 000	3.1 and 4.6	Surface water Waste heat	72 (18/90) 55 (35/90)	R134a (103 %)	20
Famiglietti et al. (2022)	Vapor compression	15 000	2.2	Groundwater	70 (20/90)	R134a (103 %)	21
Pakere et al. (2022)	Vapor compression	N/S	N/S	Waste heat	N/S	R134a (N/S)	N/S
Cluster No. 3 – Small-size heat pump (CLCA)							
Pedinotti et al. (2019)	Vapor compression	10	2.25 4.17	Air source Ground source	N/S	R134a	10
Naumann et al. (2022)	Vapor compression	5	3.26	Air source	60 (−10/50)*	R134a	20
Famiglietti et al. (2023)	Vapor compression Absorption	6.3 to 19.6 3.7 to 14	2.21 to 2.52 1.33 to 1.37	Air source	45 and 75 (−10/35) & (−10/65)*	R134a (105 %) Water-ammonia (0 %)	21

* Information is not explicitly reported in the paper but is derived from other sources or inferred by the authors.

used in the heat pump is seldom mentioned, with the exception of Zeilerbauer et al. (2023) (piston compressor) and Nitkiewicz et al. (2014) (screw compressor). It can be assumed that a turbo compressor is most likely used for capacities higher than 1 MW. In comparison, piston or screw compressors are most likely used below 1 MW. For HPs with smaller capacities, piston, scroll or rotary compressors are the usual options.

- Absorption heat pumps appear 3 times in the literature review: twice in the large-size heat pump category and once in work on small-size heat pumps (CLCA).
- Stirling heat pumps appear in 3 works on HTHPs: the advantages of this type of system are mainly high temperature lifts and flexible operation.

Some works compare two heat pump typologies, while others compare a single heat pump technology with a boiler.

The number of papers addressing the analysis of each technology represents, to a certain extent, the market development, which sees vapor compression heat pumps used in applications ranging from a few kW to several MW in capacity and covering a wide range of temperature lifts and temperature levels. Absorption heat pumps can be found in different capacities but are usually limited in the heat sink temperature, mainly due to thermodynamic reasons and corrosion constraints associated with the working fluid used (e.g., lithium-bromide). In contrast, the Stirling cycle finds limited application in the high-capacity and high-temperature ranges (i.e., companies like Olvondo or Enerin from Norway).

6.8. Efficiencies and temperature lift

When conducting an LCA study on a heat pump application, its efficiency is one of the key parameters. Efficiency directly impacts the use phase, which is usually the largest contributor [24,27,28,32,36,37,59].

Additionally, the efficiency of heat pumps depends on working conditions, namely the temperatures of the heat source and sink and the degree of part-load operation. The latter information is seldom provided because it depends on the design approach and can be effectively derived only through a yearly or seasonal analysis. The temperature levels are often presented and usually condensed as the temperature lift, a parameter given by the difference between the heat sink outlet and heat source inlet temperatures. The strong correlation between COP and temperature lift [6] represents useful information for contextualizing the heat pump's efficiency.

The analyzed papers in this review cover various temperature lifts and working conditions for vapor compression heat pumps. Fig. 4(a) shows the temperature lift vs. the COP. The scatter plots for each cluster were interpolated with power functions presented in the graph with the coefficient of determination (R^2). Fig. 4(b) presents the COPs of the HPs as a function of the temperature lift and the heat sink temperature. The points related to each HP are colored according to the COP value declared by the authors, while the shape indicates the HP cluster. The colored background is obtained by calculating a monotone function that interpolates the COP values of the HPs (a second-degree polynomial for the x-axis and a linear profile for the y-axis). The color scale obtained for the x-axis ranges from the highest value of COP (9.7) to the lowest value (1.9). From the chart, it can be appreciated that the COP depends on both thermal lift and sink temperature but that the latter has a significantly lower impact than the former, confirming that the thermal lift can be used as the main indicator to describe the operating conditions of the HP.

6.9. Working fluids and estimated service life

The choice of refrigerant impacts the outcome of the environmental profile on a heat pump due to the possible global warming potential of the molecule or the production phase.

- R134a is the most common refrigerant in the three clusters (1 530 $kgCO_2eq$ / kg according to the Environmental Footprint 3.1 method). This is motivated by the wide use of this refrigerant for heat pumping applications, even if alternative refrigerants are becoming more popular after the regulations on the progressive ban of fluorinate gases [60,61].
- R1336mzz is one of these alternative refrigerants, with a Global Warming Potential (GWP) 100 of about 7 ($kgCO_2eq$ / kg) [62], and is used as an alternative for high-temperature applications.

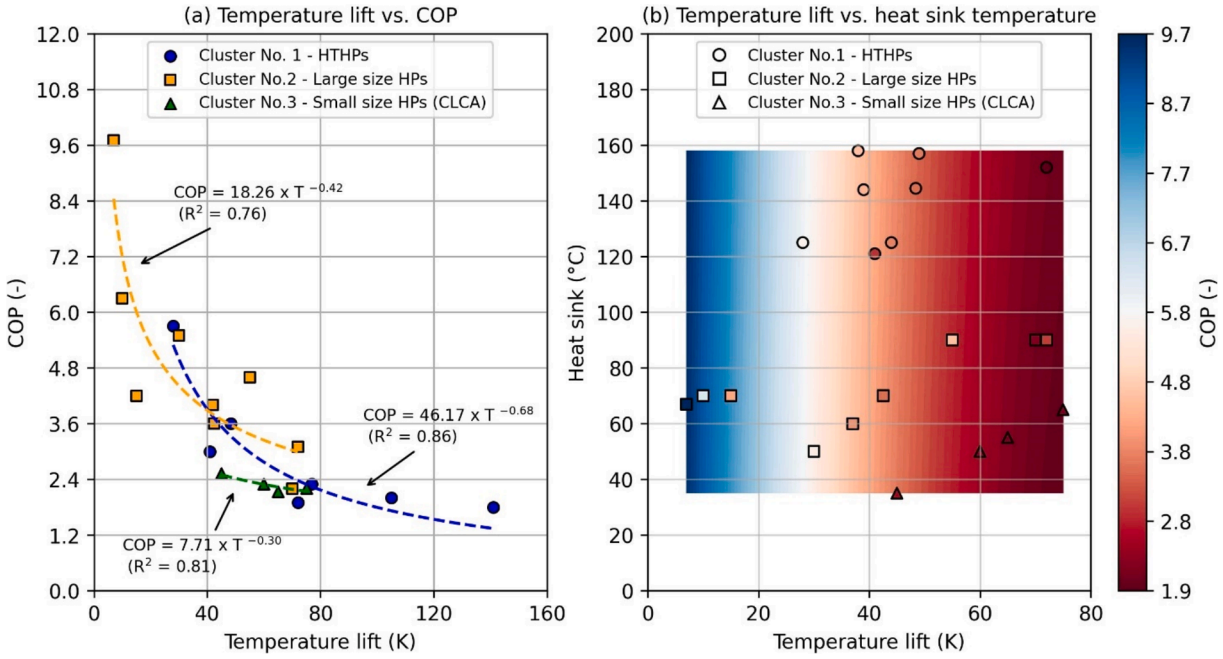

Fig. 4. Technology descriptions for vapor compression heat pumps: (a) temperature lift vs. COP, highlighting clusters, and (b) temperature lift vs. heat sink temperature, highlighting COPs and clusters (HTHPs, Large-size HPs, Small-size HPs).

- R1234ze is another low-GWP refrigerant (< 10 $kgCO_2eq$ / kg), considered in two studies on large-size heat pumps at a supply temperature of about 70 °C.
- Helium (R704) is a natural refrigerant with zero GWP, suitable for high-temperature applications. Given the extremely low critical temperature, it can be used only in gas cycles, as the Stirling Engine is considered in three of the works in this review.
- CO_2 (R744) is also found in high-temperature applications. This refrigerant has a GWP equal to 1. It is used in supercritical cycles, usually characterized by high pressures which limit the application up to 120 °C [62].
- Water-ammonia (R718-R717) is a mixture used in the absorption heat pumps. Studies on this technology are found for large (two contributions) and residential (one) heat pumps, with a maximum supply temperature of about 70 °C due to the technical limitation of this technology.

Table 5 presents refrigerant gas leakage for vapor compression HPs in disaggregated form, i.e., distinguishing the leakage for each life cycle stage with respect to what is reported in Table 4. The leakages for the manufacturing phase are considered only by Famiglietti et al. (2021, 2022, and 2023), Pozzi et al. (2021), Spirito et al. (2021), and Naumann et al. (2022) and equal to 3 % of the charge of the machine. The annual leakage in the use phase ranges from 1 % to 6 % for Zeilerbauer et al. (2023) and Naumann et al. (2022), respectively. The end-of-life (EoL) values range from 15 % to 20 %, according to Jovet et al. (2022 and 2024) and Famiglietti et al. (2021, 2022, and 2023), Pozzi et al. (2021), Spirito et al. (2021), respectively.

Table 5
Refrigerant leakage rates considered by authors for vapor compression heat pumps.

Authors	Manufacturing (%)	Use phase (% annually)	End of Life (EoL) (%)
Cluster No. 1 – High-Temperature heat pumps			
Jovet et al. (2022)	N/S	5 %	15 %
Zeilerbauer et al. (2023)	N/S	1 %	N/S
Jovet et al. (2024)	N/S	5 %	15 %
Cluster No. 2 – Large-size heat pumps			
Nitkiewicz et al. (2014)	N/S	N/S	N/S
Bartolozzi et al. (2017)	N/S	N/S	N/S
Famiglietti et al. (2021)	3 %	4 %	20 %
Jeandaux et al. (2021)	N/S	N/S	N/S
Mahon et al. (2021)	N/S	N/S	N/S
Pozzi et al. (2021) *	3 %	4 %	20 %
Pratiwi et al. (2021)	N/S	3.5 %	N/S
Spirito et al. (2021) *	3 %	4 %	20 %
Famiglietti et al. (2022)	3 %	4 %	20 %
Pakere et al. (2022)	N/S	N/S	N/S
Cluster No. 3 – Small-size heat pump (CLCA)			
Pedinotti et al. (2019)	N/S	2 %	N/S
Naumann et al. (2022)	3 %	6 %	0 %
Famiglietti et al. (2023)	3 %	4 %	20 %

* Information is not explicitly reported in the paper but is assumed by the authors.

6.10. Life cycle assessment main results

This section reports the main environmental findings of the review of the final 19 articles described in the Material and Methods section, in particular:

- The main life cycle stage contributors.
- The background LCI databases used.
- The average environmental profile of the HPs analyzed.
- Comparison results with reference technologies conducted within the articles.

Main life cycle stage contributors.

Table 6 highlights the main life cycle GWP results per life cycle phases. In each specific life stage, the number of articles that included the given stage, the number of scenarios (i.e., papers can provide different results by changing the operation configuration, the geographical location, etc.), and the average, minimum, and maximum contribution of the stage are reported. The number of articles and scenarios is calculated based on the papers that explicitly show the specific life cycle stage contribution or where it was possible to assume it. The articles from which the data were extracted to populate Table 6 are: Bartolozzi et al. (2017), Famiglietti et al. (2021), Mahon et al. (2021), Pozzi et al. (2021), Spirito et al. (2021), Famiglietti et al. (2022), Naumann et al. (2022), Famiglietti et al. (2023), all of them belonging to Cluster No. 2 or No. 3.

The studies agree that the use phase is the main contributor, with an average value of 94.6 % (ranging from 71.7 % to 99.44 %). The variation depends on:

- The environmental profile of the energy vector (i.e., related to geographical location and modeling approach, i.e., ALCA, CLCA, rLCA, or pLCA).
- The efficiency of the HPs.
- The contribution of the other phases.

Maintenance is the second contributor, with an average value of 2.8 % with a maximum value of 17.8 %. This high value is related to the high GWP of the refrigerant and the quantity of leakages considered during the operational phase. The production of components has the third highest impact, mainly related to the contribution of metal component productions. The impact of the other phases is negligible except, in some cases, the End-of-Life (EoL), which has an average contribution of 0.2 %, with a minimum value of −1.5 % and a maximum value of 9.2 %. The minimum value with a negative sign is related to the CLCA results, thanks to the potential benefits of avoiding activities (e.g., end of life stages) due to the use of secondary raw materials derived from reuse, recovery, and recycling processes. The maximum value is still related to refrigerant leakages, estimated to be up to 20 % of the total charge.

For the other environmental impact categories, the contribution of the six stages varies significantly, although the use stage remains the most relevant (average value equal to 69.9 %). For example, for the “Material Resources: Metals/Minerals,” the significant stages are

Table 6
Contribution per life cycle stage for global warming potential impact category.

Life cycle stage	No. articles	No. scenarios	Average contribution (%)	Min value (%)	Max value (%)
Production of components	8	29	2.1 %	0.0 %	15.0 %
Manufacturing	5	25	0.4 %	0.0 %	1.1 %
Distribution	5	25	0.1 %	0.0 %	0.4 %
Use phase	8	29	94.6 %	71.7 %	99.4 %
Maintenance	6	27	2.8 %	0.0 %	17.8 %
End of Life	7	28	0.2 %	−1.5 %	9.2 %

"component production," equal to 22.6 % (with a max value of 37.8 %), and "manufacturing," equal to 2.9 % (with a max value of 14.6 %). This highlights the importance of other life cycle phases over the use phase in the analysis.

The "Material Resources: Metals/Minerals" (MRM) was chosen among the other impact categories in the analyzed articles. The impact category was considered relevant in implementing the normalization of the results. The normalized results are obtained by normalizing the impact category values, thus dividing them by a selected reference. The Environmental Footprint (EF) 3.0 method developed by the Joint Research Centre – European Commission [63], for example, utilizes the global annual released mass of each impact category per person (considering a world population equal to 6 895 889 018) to calculate the normalization factors. The MRM impact category indicator estimates the abiotic depletion potential. The characterization model is a function of the resources' natural reserves under evaluation and their extraction rate in the product system processes [64].

The background life cycle inventory databases used.

The distribution of the background Life Cycle Inventory (LCI) databases used for the studies included in this review is reported in Fig. 5(a). The sum is higher than 19 (23) because 4 papers used more than one database, i.e., Zeilerbauer et al. (2023), Mahon et al. (2021), Pratiwi et al. (2021), and Naumann et al. (2022).

It can be noticed that 19 out of 23 studies are based on ecoinvent [46], using the libraries detailed below:

- 8 authors did not state which system model they used, i.e., Kahn et al. (2020 and 2021), Jovet et al. (2024), Zeilerbauer et al. (2023), Högnabba et al. (2024), Bartolozzi et al. (2017), Mahon et al. (2021), and Pratiwi et al. (2021).
- 6 authors adopted the attributional library "Allocation, cut-off by classification," i.e., Nitkiewicz et al. (2014), Famiglietti et al. (2021), Pozzi et al. (2021), Spirito et al. (2021), Famiglietti et al. (2022), and Naumann et al. (2022).
- 1 author used the attributional library "Allocation at the Point of Substitution – APOS," i.e., Pakere et al. (2022). Differently from the cut-off by classification in APOS, the responsibility over wastes is shared between producers and subsequent users (in cut-off by classification, wastes are the producer's responsibility).
- 4 authors adopted the consequential library "Substitution, consequential, long-term," i.e., Jovet et al. (2022), Pedinotti et al. (2019), Naumann et al. (2022), and Famiglietti et al. (2023).

Pratiwi et al. (2021) integrated the ecoinvent library with the Waste Electrical and Electronic Equipment (WEEE) database [65]. WEEE is a French library dedicated to the end-of-life of electrical and electronic equipments. Zeilerbauer et al. (2023) and Mahon et al. (2021) implemented the evaluation using the GaBi database [66] in addition to ecoinvent. Finally, Jeandaux et al. (2021) utilized the Environmental Footprint (EF) 2.0 database. The Joint Research Center – European Commission implements the library for the Environmental Footprint Programme [56].

For what concerns the characterization method, the choice of the authors of the studies is presented in Fig. 5(b). The characterization methods permit the evaluation of the environmental issue of concern to which LCI results may be assigned. The characterization factor is derived from a characterization model, which is applied to convert an assigned LCI result to the common unit of the category indicator (e.g., 1 kg of CH_4 to CO_2eq, the quantifiable representation of global warming potential, etc.). The methods can be classified into the methodologies that list impact categories assigned to the inventory results (midpoint categories, like the case of global warming potential mentioned) and which can be further bundled into damage categories (endpoint categories, i.e., human health effects evaluated in disability-adjusted life year, etc.). In detail:

- Midpoint categories:
  - 7 articles used the Environmental Footprint (EF) method, i.e., the characterization method suggested by the European Commission. Since the updated version of the method, EF 3.1, came out in 2022, the articles analyzed include the previous version, 3.0. Probably not yet implemented within commercial software at the time of writing of the most recent articles analyzed. The authors who used the EF 3.0 method are: Jovet et al. (2024), Famiglietti et al. (2021,

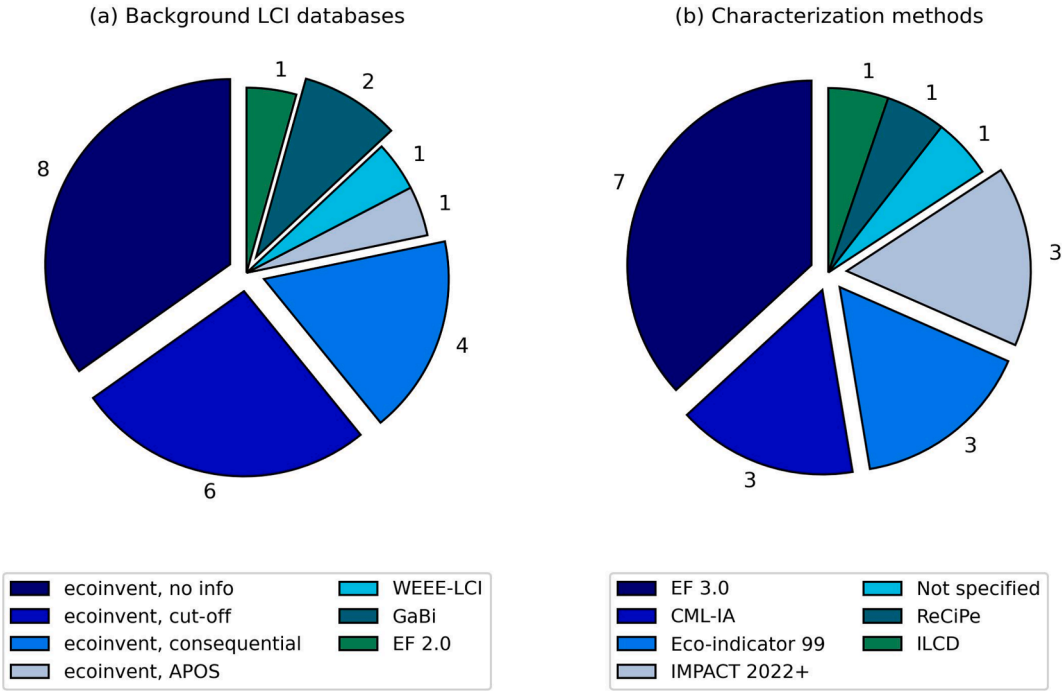

Fig. 5. (a) Background life cycle inventory databases per article and (b) characterization methods per article.

2022, and 2023), Jeandaux et al. (2021), Pozzi et al. (2021), and Spirito et al. (2021).
  - o 3 articles used the CML method created by the University of Leiden (the Netherlands) in 2001 [67], i.e., Zeilerbauer et al. (2023), Mahon et al. (2021), and Naumann et al. (2022).
  - o 1 article used the ReCiPe midpoint 2016H [50], i.e., Pratiwi et al. (2021).
  - o Bartolozzi et al. (2017) used the ILCD method [68] developed by the Joint Research Centre – European Commission before the EF method.
- Endpoint categories (both the methods considered superseded):
  - o 3 articles used the Eco Indicator 99, i.e., Kahn et al. (2020 and 2021) and Nitkiewicz et al. (2014).
  - o 3 articles used the IMPACT 2002 +, i.e., Högnabba et al. (2024), Pakere et al. (2022), and Pedinotti et al. (2019). Högnabba et al. (2024) also presented the results at the midpoint level.

Finally, Jovet et al. (2022) implemented a carbon footprint analysis (only GWP indicator) without specifying the characterization method.

Average environmental profile of the HPs.

Fig. 6 shows the results concerning three midpoint category indicators:

(a) Global Warming Potential (GWP).
(b) Acidification Potential (AP).
(c) abiotic depletion potential, Material Resources: Metals/Minerals (MRM).

The results are subdivided per cluster and heat pumps' nominal heating capacity (P_n). The outcomes are obtained using the standardization method described in Section 2.3. In addition to climate change, the other two indicators were selected based on normalization, as explained for life cycle stage contributions. The outcomes presented in Fig. 6(a) are related to the scenarios evaluated by the articles that used the midpoint characterization method plus the values presented by Högnabba et al. (2024). The results are not corrected, even if some methods used IPCC 2013 (i.e., EF 3.0, CML, ReCiPe) and others IPCC 2007 (i.e., ILCD), i.e., using slightly different GWP values for some greenhouse gases. However, the difference was not considered relevant for the purpose of this analysis.

Jovet et al. (2022 and 2024) and Jeandaux et al. (2021) are excluded from the plots. The former is because it provides results using sustainable limits defined by the authors, thus not showing midpoint category indicator outcomes. The latter is because it does not present results related to the HP but for district heating supplied by other technologies.

The articles selected for Fig. 6(b) are the same as Fig. 6(a), excluding Mahon et al. (2021) and Naumann et al. (2022). Mahon et al. (2021) do not present the results for the AP indicator, and Naumann et al. (2022) provide the outcomes for the other indicators (beyond GWP) in %. As anticipated in Section 2.3, the results obtained by EF 3.0, ILCD, ReCiPe, CML-IA, and IMPACT 2002 + are corrected utilizing the correction factors provided by Rybaczewska-Błażejowska and Jezierski (2024) [69]. The articles selected for Fig. 6(c) are the same as Fig. 6(b) except for Högnabba et al. (2024) and Pratiwi et al. (2021). The exclusion is because the correction factors for abiotic depletion potential do not cover ReCiPe and IMPACT 2002 + .

The three subplots of Fig. 6 also indicate the arithmetical average value for each cluster. The GWP average values range from 121 to 151 (g CO_2eq / kWh_{th}) – Fig. 6(a). As mentioned, the variation depends mainly on the environmental profile of the energy vector utilized in the thermodynamic cycles (i.e., natural gas, electricity, etc.) and the efficiency of the HP. The higher value is calculated by Högnabba et al. (2024) – Cluster No. 1 (456 g CO_2eq / kWh_{th}), where the vapor compression HP (COP equal to 1.8) is driven by Poland's electricity (approx. 70 % of electricity is produced by coal and lignite with a climate intensity over 1 000 gCO_2eq / kWh_e). The lower value is still calculated by Högnabba et al. (2024), obtained under the assumption of a climate profile of 8 gCO_2eq / kWh_{th} for a vapor compression HP (COP

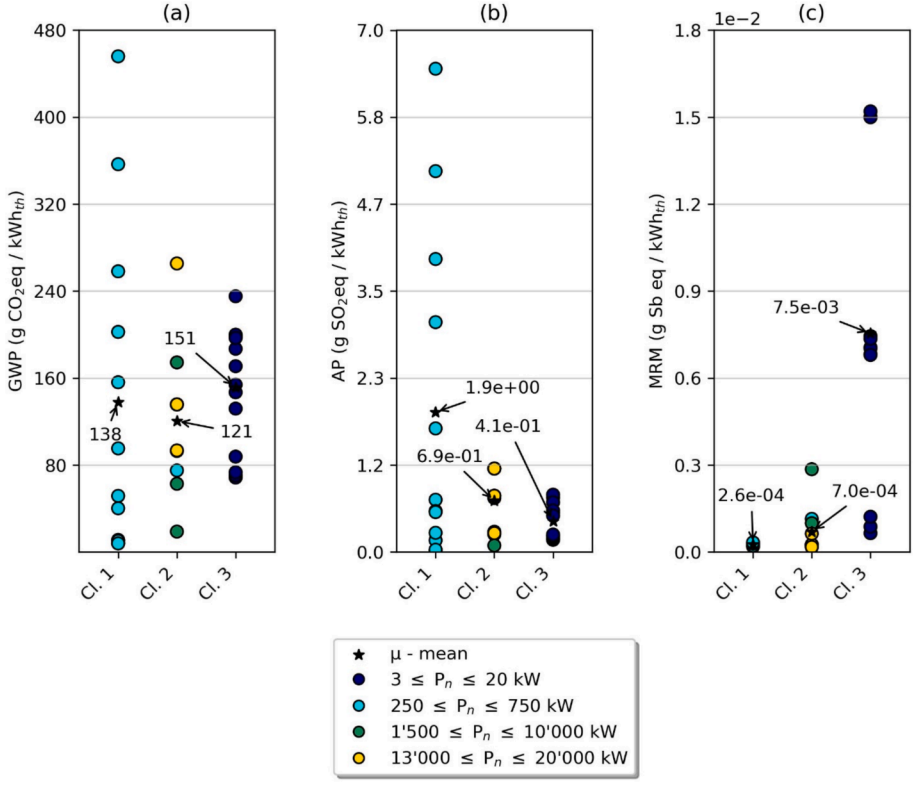

Fig. 6. Midpoint category indicators are shown per kWh_{th} generated: (a) Global Warming Potential, (b) Acidification Potential, and (c) Material Resources: Metals/Minerals. The results are subdivided per cluster and nominal heating capacity of the heat pumps.

2.3) driven by Sweden's electricity (approx. 28 % from nuclear, 43 % from hydro, and 19 % from wind).

The Acidification Potential (AP), shown in Fig. 6(b), ranges from 0.4 to 1.9 (g SO_2eq / kWh_{th}) as average values. The contribution is related to the coal and fuel oil consumption used for electricity production; thus, vapor compression HPs with low COPs, installed in countries where the two sources are still present in the electricity generation mix (e.g., Poland and Germany evaluated by Högnabba et al. 2024), have a higher contribution to this indicator. The Material Resources: Metals/Minerals (MRM), presented in Fig. 6(b), have a contribution from 0.0003 to 0.008 (g Sbeq / kWh_{th}). The amount of minerals and metals used within the product systems affects the outcome of this indicator. As mentioned above, the contribution is not strictly linked to the use phase of the machine; the component productions also play an important role. In particular, the subplot shows the higher values within Cluster No. 3 (equal to 0.015 g Sbeq / kWh_{th}), probably due to the higher mass per kW of smaller-capacity heat pumps. Famiglietti et al. (2023) evaluate gas absorption HPs thermally driven by green hydrogen and the copper used in renewable energy systems for electricity production, mainly linked with photovoltaic plants, which have the responsibility to affect the final results, as well as the components of the machine itself.

Comparison results with reference technologies.

The last analysis of this review provides, divided by cluster, a comparison between the average impact of the heat pump and one of the alternative technologies. The results, reported in Table 7, are based on the reference technologies considered in the 19 articles. The reference technologies are selected based on what is reported within the 19 articles. The selection is limited to boilers supplied with different energy vectors. District heating networks and CHP plants were excluded because they are affected by multi-functionality; therefore, the values from the various articles cannot be easily averaged.

The outcomes show that the HPs have, on average (−58 %), a better climate profile (GWP) concerning natural gas, fuel oil, and liquid petroleum gas (LPG) boilers. In contrast, the results are higher than those of green H_2 (+38 %) and solid biomass boilers (+ 66 % to + 419 %). Concerning the AP, HPs have (i) a worse result concerning natural gas, fuel oil, LPG, and green H_2 boilers (+124 %) and (ii) a better profile than biomass boilers (−64 %). Finally, analyzing the MRM, the HPs have a worse profile than natural gas, fuel oil, LPG, and biomass boilers (+974 % on average) and a better profile compared to green H_2 boilers (−97 %).

The authors would like to stress the importance of carefully using the results shown in Table 7. For example, the values of vapor compression cycle HPs can vary significantly depending on the electricity generation mix; e.g., Famiglietti et al. (2022) – Cluster No. 2 evaluate a heat pump powered with electricity generated by natural gas CHP. Therefore, the GWP, AP, and MRM results are comparable to those of a natural gas boiler because the energy vector used is the same, i.e., natural gas for both boiler and CHP, in this latter, used to generate the electricity that supplies the HP. The environmental profile of the electricity was calculated using the exergy partitioning method to allocate the burdens between electricity and heat produced by the CHP. The exergy method allocates approximately 85 % to 90 % of the impacts to the electricity.

7. Conclusions

This paper reviewed 19 articles on the environmental Life Cycle Assessment (LCA) of heat pumps, selected with a systematic literature review based on Scopus, Web of Science, and Google Scholar databases. The determined 19 final papers feature a total of 637 scenarios classified into three clusters:

(1) Hight temperature heat pumps with heat sink temperatures greater than or equal to 100 °C (with applications in the industry).
(2) Large-size heat pumps (equal or greater than 300 kW_{th} nominal heating capacity) with heat sink temperature between 50 and 100 °C (with application in district heating network).
(3) Medium and small-size heat pumps (lower than 300 kW_{th} nominal heating capacity) that are modeled using the consequential approach.

All scenarios were analyzed in depth, and the data from each article was extracted and classified into tables. The analysis revealed that the life cycle assessment studies apply a rather narrow approach and lack of variability in modeling. In particular, it can be concluded that:

- 100 % of the papers used process-based life cycle inventory modeling.
- Only 1 out of 19 papers implemented a stochastic analysis.
- The prospective life cycle assessment is limited to electricity or gas further scenarios.
- The consequential modeling for medium and small-size heat pumps is applied in only 3 articles.
- The leakages of refrigerants range to 3 % (manufacturing), 1–6 % (use phase), and 0–20 % (end of life) of the total charge.
- Lower global warming potential refrigerants are becoming more popular after the regulations on the progressive ban of fluorinate gases; within the articles investigated, the authors found R1336mzz, R1234ze, R704 (helium), R744 (CO_2), and R718-R717 (water-ammonia).
- Global warming potential, Acidification potential, and Abiotic depletion potential range from 121 to 151 (g CO_2eq / kWh_{th}), 0.41–1.90 (g SO_2eq / kWh_{th}), 0.26–7.50 (mg Sb / kWh_{th}), respectively, for cluster No.1, 2, and 3.
- The use phase of a heat pump is the main contributor per life cycle stage for global warming potential impact, averaging 94.6 % (ranging from 71.7 % to 99.44 %). The other phases contribute to 2.1 % (production of components), 0.4 % (manufacturing), 0.1 % (distribution), 2.8 % (maintenance), and 0.2 % (end of life).

Table 7
Comparison of HP profiles with reference technologies.

Cluster	Average value HP	Natural gas boiler	Fuel oil boiler	LPG boiler	Biomass (solid) boiler	Green H_2 boiler
Global Warming Potential (g CO_2eq / kWh_{th})						
No. 1	138	263 (+90%)	400 (+190%)	–	13 (−91%)	–
No. 2	121	286 (+137%)	373 (+208%)	345 (+185%)	73 (−40%)	88 (−27%)
No. 3	151	281 (+86%)	–	–	–	–
Acidification Potential (g SO_2eq / kWh_{th})						
No. 1	1.90	0.53 (−72%)	0.43 (−77%)	–	0.76 (−60%)	–
No. 2	0.69	0.61 (−12%)	0.85 (–23%)	0.63 (−9%)	0.72 (+4%)	0.28 (−60%)
No. 3	0.41	0.19 (−53%)	–	–	–	–
Abiotic depletion potential – Material Resources: Metals/Minerals (mg Sb / kWh_{th})						
No. 1	0.26	0.01 (−97%)	0.01 (−97%)	–	0.02 (−91%)	–
No. 2	0.70	3.10 (+343%)	2.05 (+192%)	0.83 (+19%)	2.74 (+291%)	22.73 (+3 148%)
No. 3	7.50	1.59 (−79%)	–	–	–	–

* Percentage values in the table were calculated as differences between reference technologies and average HP values and divided by the average HP values.

Moreover, there is a lack of description and simulation of the heat pumps under evaluation. Less than 50 % of the works report information about the heat pump relevant to a life cycle assessment study, such as heat source and sink temperatures, efficiencies (coefficient of performance and gas utilization efficiencies), and their dependence on the working condition, compressor typology, refrigerant, etc. Given their impact on the life cycle assessment outcomes, it is recommended that the thermodynamic parameters and behavior of the heat pumps be properly described and simulated (using either a mathematical model, a performance map, or monitoring data) for future research, to make the models more transparent and replicable. In addition, a stochastic evaluation shall be included in the analysis to reduce and highlight the uncertainty of the final results (especially the global sensitivity analysis).

Finally, high-temperature heat pumps shall also be investigated using the consequential life cycle assessment approach. Attributional life cycle assessment is not designed to study the effect of changes in production systems, but it is typically applied to hot-spot identification and generic consumer information. On the contrary, consequential life cycle assessment examines how the relevant physical flows will change in response to a change in demand for the analyzed product.

High-temperature heat pumps use heat, often recovered from cogeneration systems or waste heat. In these cases, applying the consequential life cycle assessment approach would allow a better understanding of the environmental consequences of the decision related to installing the heat pump in an industrial production process. This would increase the demand for electricity from the national grid, change the operation of a combined heat and power plant, and potentially avoid the discharge of the waste heat used as a low-temperature source, e.g., via dry cooler machines, and the energy consumption associated with the process.

Future research directions can extend to high-temperature heat pumps the empirical law relationships, as done by Caduff et al. (2014) [70] and Autelitano et al. (2023) for appliances and refrigerant gases.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used Grammarly software in order to check the spelling and grammar during the article's writing process. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Jacopo Famiglietti: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Leonardo Acconito:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Cordin Arpagaus:** Writing – review & editing, Investigation. **Tommaso Toppi:** Writing – review & editing, Writing – original draft, Validation, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2025.100947.

Data availability

Data will be made available on request.

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